A Map of the Northern Sky: The Sloan Digital Sky Survey in Its First Year

Eva K. Grebel

Max Planck Institute for Astronomy
Königstuhl 17, D-69117 Heidelberg, Germany
grebel@mpia-hd.mpg.de

Abstract

The Sloan Digital Sky Survey (SDSS) is the largest and most ambitious optical CCD survey undertaken to date. It will ultimately map out one quarter of the sky with precision photometry in five bands, high-quality astrometry, and spectra of all galaxies and quasars brighter than certain limiting magnitudes. The scientific potential of the SDSS is enormous and addresses a wide variety of astrophysical key questions. After a proprietary period the reduced and calibrated data are made available to the astronomical community as a whole.

The SDSS is run by an international consortium involving universities and research institutions. One of the participating partners is the Max Planck Institute for Astronomy in Heidelberg. Already in its first year the SDSS has led to a number of spectacular scientific discoveries. In this paper, we will introduce the SDSS survey, discuss its scientific potential, highlight important science results, and present the Calar Alto key program for SDSS follow-up studies.

1 Introduction

Sky surveys have a tradition dating back many centuries. Early catalogs and charts were based on eye estimates of positions and luminosities, which gained considerably in depth and accuracy with the introduction of telescopes and measurement tools such as the meridian circle. The invention of photographic plates enabled astronomers to record large areas of the sky efficiently and objectively. Digitized versions of optical photographic all-sky surveys are presently widely used and are often available on-line, accompanied by catalogs with detailed photometric and astrometric information both for point sources and extended objects. Spectroscopic follow-up surveys resulted in spectral classification of bright stars, proper motions, or classification and redshifts of luminous galaxies. The optical surveys are complemented by all-sky surveys in other wavelength ranges, which continue to gain in sensitivity and resolution.

The Sloan Digital Sky Survey (SDSS) is a large new optical survey that is purely CCD-based. The SDSS is expected to ultimately cover up to 10,000 square degrees centered on the north Galactic cap ($\alpha = 12^{\rm h}20^{\rm m}$, $\delta = +32°30'$) and three great circle slices of a total of 225 square degrees near the south

Galactic cap ($\alpha = 20.7^{\mathrm{h}}$ to 4^{h} at $\delta = 0°$; $\alpha = 20.7^{\mathrm{h}}$ to 22.4^{h} at $\delta = -5.8°$; $\alpha = 22.4^{\mathrm{h}}$, $\delta = 8.7°$ to $\alpha = 2.3^{\mathrm{h}}$, $\delta = 13.2°$). The total area corresponds to one quarter (π steradians) of the sky. The scan regions were selected to avoid areas of high Galactic extinction. The SDSS provides 5-filter photometry, astrometry, and spectroscopy. It is estimated that the imaging survey will ultimately comprise $\sim 8 \cdot 10^7$ stars, $\sim 5 \cdot 10^7$ galaxies, and $\sim 10^6$ quasars with high-quality photometry.

The participating institutions in the SDSS collaboration and some of the rules under which the collaboration operates are presented in Section 2. Technical details on the SDSS and a summary of its data products are given in Section 3.

The SDSS camera saw first light in June 1998. After the commissioning phase regular operations began in April 2000. Calibrated SDSS data will be made publicly available after a proprietary period, benefiting the astronomical community as a whole. The first incremental data release is scheduled for June 2001. The SDSS project will continue to take data over a total of five years.

The SDSS is unprecedented in its combination of depth, homogeneity, and area coverage. Its scientific potential is enormous and allows one to address a wide variety of astrophysical key questions. It provides an invaluable database for areas such as local star formation, stellar and galaxy luminosity functions, Galactic structure, low-surface brightness galaxies, galaxy evolution, clusters of galaxies, lensing, large-scale structure, and cosmology.

In this paper we attempt to summarize important scientific findings derived from SDSS data so far (Section 4) and present the Calar Alto key project for SDSS follow-up observations (Section 5).

2 Survey Participants and Operations

The SDSS is an international project with meanwhile 11 participating institutions in the USA, Japan, and Germany. The current institutional participants are the Fermi National Accelerator Laboratory, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the University of Chicago, the United States Naval Observatory, and the University of Washington. About 200 astronomers (including students) are involved in various aspects of SDSS research.

A collaboration of this size requires a well-defined set of rules and responsibilities in order to function. Data access and usage are subject to a mutually agreed upon set of guidelines. Planned science projects are announced within the collaboration to give all interested parties an opportunity to join and to avoid conflicts of interest. Publications are reviewed within the collaboration before submission. At the US universities that originally started the SDSS every faculty or staff member and their students and postdocs may work with SDSS data if they desire for as long as they work at these SDSS institutions.

At institutions that joined later the number of participants is limited by memoranda of understanding. There is a group of so-called external participants who are not at SDSS institutions but who were awarded data rights for specific projects. Finally there are "builders," a term that comprises both scientific and technical personnel that contributed significantly to the survey in its initial phase. Builders retain data rights even when leaving SDSS institutions and may request co-authorship on any SDSS publication they wish.

MPIA joined the SDSS in 1999. Eight people (including two participants as well as students and postdocs) are actively working on SDSS projects. As an in-kind contribution to the SDSS, MPIA has begun a five-year key project for SDSS follow-up studies at Calar Alto (Section 5). MPA joined the project in 2001. Other German participants include external collaborators at the Max Planck Institute for Extraterrestrial Physics, who contribute through the ROSAT All-Sky Survey (RASS).

3 SDSS Technical Information

The SDSS uses a dedicated 2.5-m telescope at Apache Point Observatory ($l = 32°46'49.30''$ N, $b = 105°49'13.50''$ W, elevation 2788 m) in New Mexico, USA. The telescope is a f/5 modified Ritchey-Chrétien altitude-azimuth design. It allows distortion-free imaging over a 3° wide field through a large secondary mirror and two corrector lenses.

3.1 The Photometric Survey

The imaging part of the SDSS is carried out as a simultaneous five-color optical drift-scan survey. Drift scanning eliminates overhead due to read-out times and pointing offsets and minimizes adverse effects of pixel-to-pixel variations. It provides an efficient observing mode with superior flat fielding and image uniformity. The multi-filter observations reduce effects of sky background variations and ensure that all data of a field are taken at the same airmass. On the other hand, drift scanning is limited in depth by telescope aperture and instrument sensitivity.

The five SDSS filters are a modified Thuan-Gunn system (u', g', r', i', z'; Fig. 1). They were designed to provide a wide color baseline with minimum overlap, to avoid night sky lines and atmospheric OH bands, to match passbands of photographic surveys, and to guarantee good transformability to existing extragalactic studies. The SDSS photometric system is described in Fukugita et al. (1996) and in Lupton et al. (1999).

The SDSS imaging camera consists of a rectangular array of 30 Tektronics/SITe CCDs arranged in 5 rows $\times$ 6 columns. The CCDs have 2048×2048 pixels each. The pixel size is $24 \mu m$, providing a pixel scale of $0.4''$. Typical seeing values are $1.5''$, but efforts are undertaken to improve the seeing. Each CCD provides a field of view with a width of $13.6'$. The gap between CCD columns is $12'$. Each scan (referred to as strip) covers a non-contiguous area

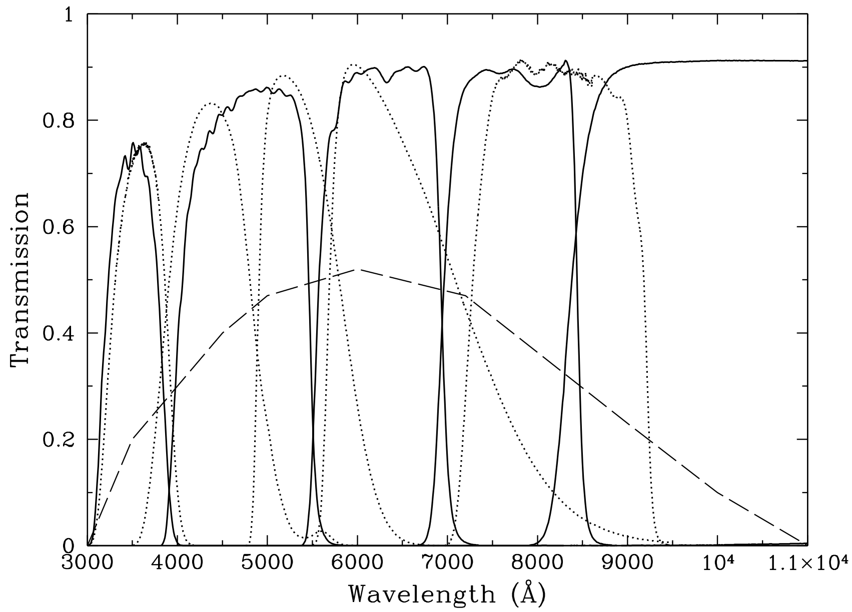

Figure 1: SDSS filter transmission curves (solid lines, from blue to red: u', g', r', i', z') compared to Johnson-Cousins filter curves (dotted lines, from blue to red: *U, B, V, R, I*). The dashed line indicates the SDSS system response.

with a width of $\sim 1.36°$. To fill the gaps a second scan is made, offset such that the overlap with the previous scan lines is $50''$ on either side. The width of completed scan (referred to as stripe) is thus $\sim 2.5°$. The engineering and technical details of the SDSS photometric camera are given in Gunn et al. (1998).

Each column of CCDs was optimized in sensitivity for its assigned filter passband. Each column is preceded and succeeded by rows of 22 smaller CCDs (2048×400 pixels) used for astrometric calibration. SDSS astrometry is based largely on the Hipparcos and Tycho catalogs and is accurate to ~ 50 mas.

When used at sidereal scanning rate the effective exposure time is 54 s, resulting in an r'-band magnitude of ~ 22.3 mag at S/N = 10 (for point sources). In the southern survey repeated imaging of the stripes is planned to allow one to search for variable objects and to reach about two magnitudes fainter.

The photometric calibration of the survey is provided by a 50-cm telescope on site (the Photometric Telescope), which measures atmospheric extinction, sky brightness, and photometric standards.

For further details, refer to the on-line SDSS Project book at

`http://www.astro.princeton.edu/PBOOK/welcome.htm` .

For a technical summary of the SDSS, see York et al. (2000).

3.2 The Spectroscopic Survey

The SDSS obtains medium-resolution spectroscopy covering the same area as the photometric survey. The spectra are taken with a multi-object fibre spectrograph with a field of view of 3°. There are 640 fibers in total, out of which ~ 480 are used for galaxies, ~ 100 for quasars, ~ 20 for other targets of special interest, ~ 32 for sky spectra, and the remainder for standards. The fibre plug plates are custom-drilled for each field, and the fibers are inserted by hand. Each fibre has a diameter of $3''$ (0.2 mm). The minimum fibre separation is $55''$. In order to account for variable galaxy density the overlap between plug plates is selected such that the spectroscopic coverage is optimized (adaptive tiling).

The SDSS spectrograph is a two-channel spectrograph covering a wavelength range of 3900 Å to 9100 Å at a resolution of ~ 3 Å ($1800 < R < 2100$). Half of the 640 fibers are fed into the blue (3900 Å – 6200 Å) spectrograph, and the other half into the red (5800 Å – 9200 Å) spectrograph. The velocity resolution is ~ 150 km s^{-1} (70 km s^{-1} pixel^{-1}) with a 10 – 15 km s^{-1} radial velocity accuracy. Exposure times are typically 45 min (3×15 min). For faint sources, S/N > 13 per Å.

The targets are selected from the photometric survey. Galaxies and quasars receive priority over stars as reflected in the number of fibre assignments listed above. SDSS is expected to ultimately obtain spectra of 900,000 field galaxies ($r' \lesssim 18.2$ mag, median redshift 0.1), 100,000 luminous red galaxies volume-limited to $z \sim 0.4$, and 100,000 quasar candidates ($g' \lesssim 19.2$ mag). Stars are only targeted when they have unusual colors. Further details can be found in the SDSS Project Book available on-line at the URL given in Section 3.2.

3.3 Data Products

Imaging data and spectra are reduced with automated pipeline packages written specifically for SDSS data.

The imaging survey yields both corrected images and photometry tables. The images are useful for, e.g., the search for low-surface-brightness features or the production of finder charts. Cut-out pixel masks, so-called atlas images, are available for each detected object in all passbands. For a quick look, combined multi-color gif images are available for each scan.

The photometry tables contain all point sources and extended sources detected in the images, their positions, fluxes and magnitudes in the five filters, Galactic foreground reddening estimated from the maps by Schlegel et al. (1998), surface brightness and integrated magnitudes where applicable, a preliminary classification (star, galaxy, etc.), profile shape, information about close neighbors, etc. For objects with SDSS spectroscopy, links to the spectra will be added.

The spectra are made available as one-dimensional, wavelength and flux calibrated tables with 4096 pixels each. Redshifts are being derived from emission lines and absorption lines separately, and both are listed. Furthermore, a list of lines, a link to the photometric and astrometric data, and an explanation of why the target was selected for spectroscopy are provided.

The SDSS data products remain proprietary within the SDSS for approximately 1.5 years in the beginning. The proprietary period for new data will be reduced as the survey progresses. The data will be released in several installments to the astronomical community through dedicated ftp and WWW servers and on CD-ROM. Mirror sites for data distribution are currently being set up at STScI, in Japan, and probably also in Germany. An easy-to-use web-browser-based query tool that will link image and catalog data is currently being developed.

The early data release of the SDSS commissioning data (5% of the imaging survey) is planned for June 6, 2001 during the summer meeting of the American Astronomical Society. The first main release is scheduled for January 1, 2003 (15% of the photometric data), followed by releases in 2004 (47% and 68%), 2005 (88%), and 2006 (everything). Since there is some time delay between imaging and spectroscopy, the fraction of released spectra will initially lag behind the amount of publicly available photometry data.

4 SDSS Science Results

Already during its commissioning phase and in its first year the SDSS has produced a wide range of scientific results as reflected by numerous conference presentations and refereed papers. A good measure of the success of a project are its scientific findings and their presentation in the refereed literature (both in terms of papers and citations). It is too early to review the number of citations of SDSS papers since the majority of them were only published in 2000 and 2001, but we can consider the number of refereed publications: More than 30 papers have been published in or submitted to refereed journals since 1999. In 1999 three SDSS science papers were published. In 2000 the number rose to 12. Within the same period, six technical papers were published in or submitted to peer-reviewed journals. In the following sections, we will try to give an overview of the various science areas addressed by the SDSS and highlight the science results obtained so far.

4.1 Large-Scale Structure

A survey like the SDSS is tailored to study large-scale structure. Indeed this is the main purpose of the SDSS. A homogeneous set of high-quality imaging data and redshifts will enable us to measure galaxy clustering over an unprecedented scale, as a function of redshift, and of galaxy type. The mass density of the universe, Ω, can be determined from anisotropies in the three-dimensional spatial galaxy distribution in the SDSS. The angular correlation function can

be determined. Large-scale peculiar velocity flows can be detected. Though the presently existing data cover only a small fraction of the final survey area, they already reveal strong clustering in the distribution of bright red galaxies out to redshifts of $z = 0.45$ and little evidence for clustering among quasars out to $z = 2.5$.

4.2 Clusters of Galaxies

Clusters of galaxies play a vital role as probes of large-scale structure and of cosmological mass density as a function of redshift. The individual constituents of galaxy clusters are useful for determining the galaxy luminosity function as a function of environment and redshift, for studying the morphology-density relation, and evolutionary probes.

The SDSS data are being used to compile a comprehensive, uniform galaxy cluster catalog through objective, repeatable, automated techniques. A variety of cluster finding algorithms are being used for this purpose including Voronoi tessellation, matched filter techniques, and other enhancement techniques (e.g., Goto et al. 2001). The usage of the very homogeneous image data combined with multi-color information aids in this enterprise. The current searches concentrate on redshifts of $0 < z < 0.6$. Follow-up studies include spectroscopic confirmation of members and correlation with other data bases such as ROSAT's RASS.

4.3 Weak Lensing

Gravitational lensing is caused by masses distributed near the line of sight to distant objects. The statistical effect of galaxy-to-galaxy lensing leads to small distortions in the shapes of background galaxies through foreground galaxies (weak lensing). In order to measure these effects one needs to make assumptions about the intrinsic shapes of the background galaxies, which should not be distorted by, e.g., star formation or interactions, or by alignment effects within galaxy clusters. Contaminating effects of this kind are best minimized statistically by sampling over large areas under good seeing conditions. Redshift information helps to determine whether background galaxies are spatially correlated. The amount of the shape distortion, or shear, is a direct measure of the mass of the foreground lens.

Fischer et al. (2000) used SDSS commissioning data to measure galaxy-to-galaxy weak lensing and detected the shear signal out to radii of $600''$ with high statistical significance. They find that the dark halos of luminous foreground galaxies extend to 260 h^{-1} kpc. The shear produced by ellipticals is stronger than the shear produced by spiral galaxies, consistent with the ellipticals being more than two times more massive.

Sheldon et al. (2001) selected galaxy clusters found in both the SDSS and in RASS data and detected highly significant shear consistent with an isothermal density profile, demonstrating that ensemble cluster masses can be measured from SDSS imaging data. They estimate that the SDSS will

ultimately contain more than 1000 galaxy clusters with RASS cross identifications, which will allow one to measure the correlation between lensing mass and cluster X-ray luminosity as well as the ratio of luminous to dark matter.

4.4 New Quasars in the SDSS

One of the primary SDSS science goals is to detect new quasars and to obtain spectra of 10^5 quasars. The pre-selection of quasar candidates is done in color space and allows one to detect, in principle, quasars with redshifts of $0 < z < 7$.

A comparison of quasars detected and spectroscopically confirmed by the SDSS with catalogs of known quasars reveals that the new SDSS quasars roughly triple the number of quasars within a given region in the sky (Richards et al. 2001a; Fig. 2). During its commissioning phase the SDSS already established several records in quasar detection: More than 150 quasars with $z > 3.5$ were found, including nine of the ten highest-redshift quasars known, and six quasars with $z > 5$. The most distant object known to date was discovered in the SDSS: a quasar with $z = 5.8$ (Fan et al. 2000; Fig. 3). Interestingly, this quasar shows already metal emission lines and evidence for a highly ionized universe only ~ 1 Gyr after the Big Bang. The derived black hole mass of this object is 3×10^9 from Eddington arguments (absolute magnitude of -27.2 at a rest-frame wavelength of 1450 Å).

In SDSS data the most distant radio-loud quasar was discovered. The number of BAL quasars was significantly increased (e.g., Anderson et al. 2001). Furthermore, a sample of intrinsically reddened quasars was found. Follow-up studies are in progress. The SDSS led to the discovery of high-redshift quasar pairs, whose de-projected separation is estimated to be < 1 kpc (e.g., Schneider et al. 2000). The detection of such pairs provides evidence of clustering at $z > 3.5$.

Ultimately the SDSS data will allow us to study the quasar luminosity function as a function of redshift at high spectral resolution and in unprecedented detail. Furthermore, the much improved quasar census will contribute significantly to studies of large-scale structure. The high-redshift quasar luminosity function seems to be considerably shallower than at low-redshift (Fan et al. 2001). Preliminary results for the quasar spatial density indicate a pronounced decrease at $z > 3.5$ and, in combination with 2dF results, a peak somewhere between redshifts of 2 and 3 (Fan et al. 2001).

The five-filter SDSS photometry is uniquely suited to determine photometric redshifts since the SDSS filters cover a wide wavelength range with little overlap. The four colors constructed from adjacent filters mimic a low-resolution objective-prism survey with $R \sim 4$ ranging from ~ 3000 Å to $\sim$ 10,000 Å (Richards et al. 2001b). These colors show a strong correlation with redshift, and little dispersion at a given redshift. Richards et al. (2001b) find that 70% of the photometrically determined redshifts are correct to within Δz $= 0.2$ for $0 < z < 5$ down to a magnitude of $g' \leq 21$ mag. Hence SDSS photometry has the potential of adding 10^6 quasar candidates to the 10^5 quasars

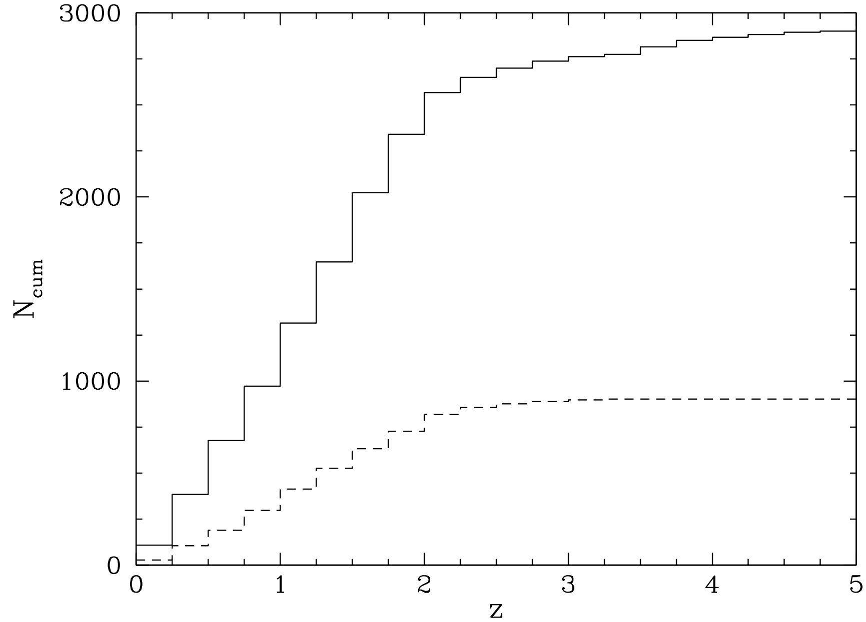

Figure 2: Cumulative number distribution (N_{cum}) of quasars within a ~ 530 square degrees equatorial stripe as a function of redshift z. The dashed line denotes all quasars previously listed in the pre-SDSS literature. The solid line comprises all these and the new quasars detected by the SDSS. The SDSS detections increased the number of known quasars in this region by 200%. Adapted from Richards et al. (2001a).

for which SDSS will obtain spectra.

Vanden Berk et al. (2001) combined more than 2200 SDSS quasar spectra to produce composite spectra covering a rest wavelength range of 800 Å – 8555 Å with 2 Å resolution and a $S/N < 300$. These spectra contain more than 80 emission lines. There is a clear trend of increased contributions from young and intermediate-age populations in the underlying host galaxies at decreasing redshift. These composite spectra are the highest-resolution, largest wavelength-range spectra existing to date and will be extremely useful for a variety of applications including template fitting and quasar continuum determinations.

4.5 Galaxy Studies With the SDSS

The SDSS is obviously a perfect tool for galaxy studies. The combination of galaxy photometry, surface profiles, structural parameters, spectra, and redshifts makes it possible to address a wide range of topics. The properties of galaxies in voids vs. groups vs. clusters can be studied with excellent statistics.

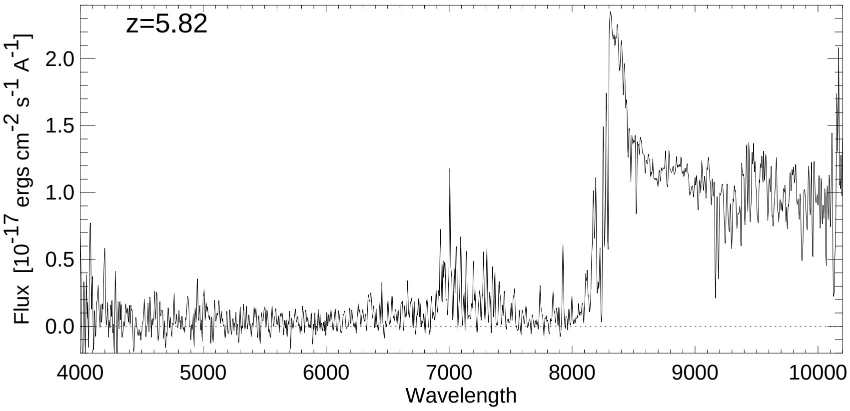

Figure 3: Spectrum of the most distant quasar known so far ($z = 5.8$; Fan et al. 2000). This spectrum was obtained with Keck II/ESI. The flux level of the Lyman α forest does not reach zero. This lack of the Gunn-Peterson trough indicates that at this redshift the universe is already highly ionized. Image credit: Richard White, Space Telescope Science Institute.

Galaxy morphology, the morphology–density relation, and galaxy luminosity functions can be investigated as a function of environment, type, and redshift. Galaxy profiles can be used for disk/bulge decomposition, studies of lopsidedness, indications of interactions, etc. The homogeneity of the imaging data makes the SDSS ideally suited for the search for low-surface-brightness galaxies and dwarf galaxies. The galaxy spectra yield a wealth of information useful for deriving star formation rates, emission and/or absorption line abundances, and the characteristics of the dominant underlying populations.

Blanton et al. (2001) determined the luminosity function for 11,275 galaxies with SDSS redshifts and absolute magnitudes in the range of approximately -23 mag $< M_r < -16$ mag. The resulting luminosity density exceeds that of the Las Campanas Redshift Survey by a factor of two owing to the use of Petrosian magnitudes, which include a larger fraction of the total galaxy flux than uncorrected isophotal magnitudes. Luminosity functions derived by earlier surveys can, however, be reproduced when a similar isophotal magnitude criterion is used. Blanton et al. find the Schechter function to produce good fits. The low-luminosity slope is similar in all five SDSS bandpasses, while the slope α is shown to be sensitive to galaxy surface brightness, color, and morphology. Luminous galaxies generally have higher surface brightness, redder colors, and are more concentrated than less luminous galaxies, consistent with earlier results. Blanton et al. also find a strong magnitude – surface-brightness relation.

4.6 Galactic Structure Studies With the SDSS

A wide-area, multi-color, homogeneous imaging is an ideal tool for Galactic structure studies. Star counts within the vast area probed by the SDSS will lead to improved determinations of the structure and position-dependent scale heights of the Galactic thick and thin disk and the Galactic halo.

The commissioning data have been used with great success to search for substructure in the Galactic halo. These studies led to the discovery of overdensities in "A-colored stars" identified as blue horizontal branch stars and blue stragglers (Yanny et al. 2000), and RR Lyrae (Ivezić et al. 2000). Ibata et al. (2001) showed that this substructure is consistent with the expected location of the stellar tidal stream torn off the Sagittarius dwarf spheroidal galaxy that is currently being accreted by the Milky Way. As the area surveyed by the SDSS grows one expects to trace the tidal streams over larger regions, allowing us to constrain not only the dynamical history of Sagittarius, but also the mass distribution of the outer Milky Way.

Searches for stellar substructure can be carried out in arbitrary regions in the hope of serendipitous discoveries. Alternatively, one can target the surroundings of objects that may produce such substructure. Both star clusters and nearby dwarf galaxies fall in the latter category, since they may suffer tidal disruption through the Milky Way. Numerical simulations predict that possibly as many as half of the present-day Galactic globulars will not survive for another Hubble time. Prime candidates for tidal disruption are diffuse, low concentration clusters.

Among the first star clusters observed during the SDSS commissioning phase was the sparse, distant halo globular cluster Palomar 5. We searched for stellar overdensities in color-magnitude space around Pal 5 and discovered two well-defined, symmetric tidal tails around Pal 5 that subtend an arc of at least 2.6° on the sky (Odenkirchen et al. 2001). The tails show an S-shaped structure near Pal 5 and exhibit two density clumps at equal distances to the cluster center, both in accordance with expectations from N-body simulations. The stars in the tidal tails make up 34% of the cluster's stellar population, showing that the cluster is suffering heavy mass loss and may be completely torn apart after its next disk passages. The orientation of the tails allows us to constrain the cluster's orbit.

Studies of the structural parameters and a search for potential tidal tails around dwarf spheroidals around the Milky Way and other Galactic globular clusters are in progress.

4.7 Special Types of Stars in the SDSS

Stars observed by the SDSS provide an invaluable resource in their own right. While only stars that appear to be peculiar in some way (such as through unusual colors) are scheduled for SDSS spectroscopic follow-up, the five-passband photometric database allows one to perform a preliminary classification of special types of stars based on their distinctive colors alone. Stars

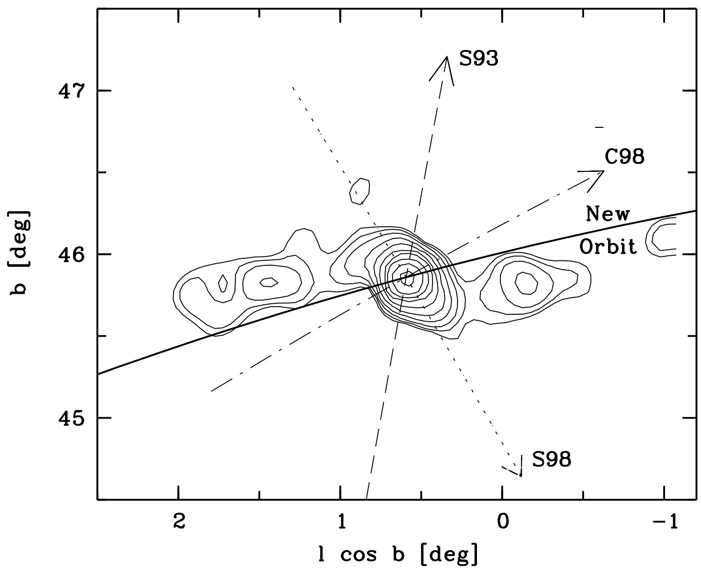

Figure 4: Contour plot of the surface density of color-magnitude-selected candidate member stars of the Galactic globular cluster Pal 5 in galactic coordinates. The overlaid arrows represent different orbital paths of the cluster according to different determinations of its absolute proper motion. The solid line presents our improved estimate of the orbit (Odenkirchen et al. 2001).

that stand out due to their colors include white dwarfs, cataclysmic variables, hot subdwarfs, carbon stars, M, L, T, and brown dwarfs.

The SDSS is rapidly increasing the white dwarf census and may as much as quintuple it. The individual white dwarfs cover a wide range of types including cataclysmic variables (22 new objects discovered at the time of writing), magnetic stars, or very cool white dwarfs, making detailed studies of the white dwarf luminosity function possible. Some of the SDSS white dwarfs are constituents of white dwarf – red dwarf pairs. Hot white dwarfs are often central stars of planetary nebulae.

The coolest white dwarf known to date was recently discovered by the SDSS (Harris et al. 2001). Very cool white dwarfs are important since they belong to the oldest objects in the universe. In order to detect these faint objects they need to be fairly nearby. The proper motion of the recently discovered, very cool (3000 K – 4000 K) white dwarf indicates that it belongs to the Galactic disk rather than the halo.

The SDSS is also improving the Galactic C star census, particularly for faint, high-latitude C stars. The latter are believed to be distant halo objects, which would make them excellent tracers of the kinematics of the Galactic halo, and of the Milky Way potential. So far 36 new C stars have been discovered, half of which are dwarf C stars. Dwarf C stars are a type of

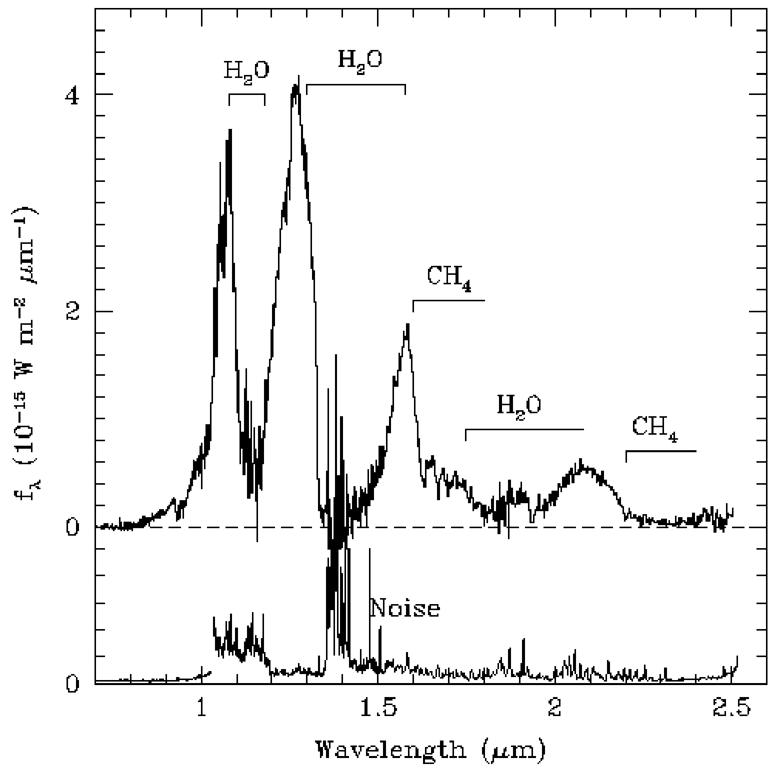

Figure 5: Spectrum of the first methane dwarf detected by the SDSS (Strauss et al. 1999). This brown dwarf is a free-floater in the field at a distance of ~ 10 pc. The strong methane and water bands in the spectrum show that it is a member of the rare class of T dwarfs. The spectrum was obtained with UKIRT. Image credit: SDSS Collaboration.

star that was only recently recognized. Owing to their faintness only nearby (within ~ 100 kpc) objects of this class have been detected so far. Preliminary findings indicate that these objects are the dominant type of C star. Together with very cool white dwarfs they may contribute significantly to the baryonic mass of galaxies. Due to their proximity proper motions can be determined for dwarf C stars, which together with their radial velocities constrains their motion.

Cool late-type stars are another type of stars whose numbers are significantly increased by the SDSS. Many of these objects lie in the same SDSS color range as high-redshift quasar candidates. The combination with 2MASS data is helping to remove ambiguities and to identify promising targets for spectroscopic follow-up. The SDSS has already discovered more than 100 new late M dwarfs, about 50 new L dwarfs, and more than 15 T dwarfs. The spectral classes L and T were added to the spectral sequence only within the past three years (Kirkpatrick et al. 1999). Low-mass stars and brown dwarfs cooler

than late M dwarfs ($\sim 1400 < T_{\rm eff} < 2000$ K) are classified as L dwarfs. In L dwarfs TiO and VO absorption decreases, while the H_2O bands increase with decreasing temperature. The T dwarf range begins at temperatures cooler than 1300 K. T dwarfs may be the link between stars and gaseous planets and are sufficiently cool to allow methane to form in their atmospheres. T dwarfs are characterized by pronounced H_2O and CH_4 absorption (Leggett et al. 2000). Very cool, red stars identified by the SDSS were recently found to establish the missing spectral transition link between the L and T classes and helped to provide a full spectral sequence for these new classes from late M to late T dwarfs (Leggett et al. 2000).

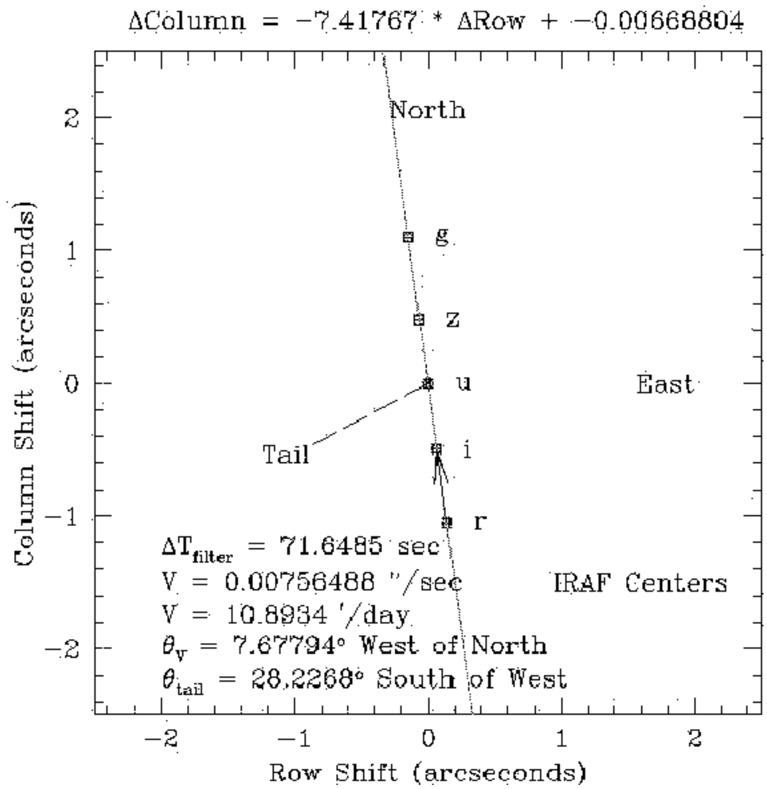

Figure 6: An illustration of the SDSS's ability to detect moving solar system objects: The motion of comet Dalcanton across the sky as it was observed by the successive filters of the SDSS imaging camera during a scan. Image credit: Julianne Dalcanton.

Two field methane brown dwarfs, or T dwarfs, have been discovered in the SDSS so far (Strauss et al. 1999; Tsvetanov et al. 2000; Fig. 5). They both lie at distances of approximately 10 pc, have estimated masses of 0.015 – 0.06 $M_{\odot}$, and ages of 0.3 to 5 Gyr. More of these rare free-floaters were detected in DENIS, 2MASS, and in proper motion surveys. Their number may amount

to a few hundred across the entire sky.

4.8 Solar System Science With the SDSS

Nearby moving objects such as asteroids and comets show clearly detected motion within an SDSS scan. The SDSS software picks out these objects automatically. The SDSS already found quite a few asteroids and its first comet (Fig. 6). This comet is one of the few objects believed to have come from the inner Oort Cloud and has its perihelion near the orbit of Jupiter (Dalcanton et al. 1999). More distant objects such as Kuiper Belt objects are too far away to have detectable motion in a single SDSS scan.

5 The Calar Alto Key Project for SDSS Follow-up

While the SDSS is still in its first year of regular operations, it has already contributed a wide range of impressive discoveries. It is also obvious that various areas of SDSS-based science need to be complemented by observations that the SDSS itself cannot provide. Infrared imaging or spectroscopy is essential for a variety of studies from quasars to low-mass stars. Stellar spectroscopy is intentionally neglected by the SDSS since cosmological problems are among its primary science goals. Certain types of SDSS follow-up studies require long-slit spectroscopy, others deeper imaging than a drift-scan survey can provide, yet again others need observations at very high angular resolution.

The SDSS scientific returns can be maximized by adding targeted targeted follow-up observations, at wavelength and spectral set-ups not covered by the SDSS itself, and by providing these capabilities at a guaranteed-time basis.

The instrumentation at Calar Alto provides a unique opportunity for such targeted follow-up observations for a variety of different programs. Of the above requirements, Calar Alto can provide infrared imaging and spectroscopy, optical longslit spectroscopy, and deep imaging. The director of MPIA therefore decided to set aside a certain fraction of observing time for a key project for SDSS follow-up studies at Calar Alto. This project is in some ways a successor of the previous MPIA key project, CADIS. Having fixed amounts of observing time allocated to this project throughout each semester during the five-year lifetime of the survey will allow sufficient flexibility to accommodate target-of-opportunity observations as well as long-term planning of follow-up observations for large SDSS science projects, thus optimizing the scientific returns. We anticipate to use 30 – 45 nights per semester for this key program, which is expected to run until 2005. As an in-kind contribution to the SDSS the MPIA is committed to making part of this observing time available to the SDSS collaboration.

The first semester of key project observations began in January 2001 with a total number of 44 nights. These nights include bright, grey, and dark

time at the 2.2-m and 3.5-m telescopes at Calar Alto. We are currently using four instruments: MAGIC for infrared imaging and spectroscopy, CAFOS for imaging and low-resolution optical spectroscopy, MOSCA for optical multi-object spectroscopy, and TWIN for optical spectroscopy at SDSS resolution and wavelength coverage, or at higher resolution.

Time is allocated on a monthly basis in order to be able to respond quickly. Incoming proposals are reviewed by the SDSS group at MPIA. The observations are carried out in service mode at Calar Alto. Service mode is particularly well suited for the SDSS follow-up projects as it allows to accommodate requests for observations in photometric conditions, good seeing, etc., to be carried out with more flexibility.

At MPIA we are currently pursuing five main SDSS projects in collaboration with other SDSS astronomers:

- Source identification of quasar and low-mass star candidates,
- Hα rotation curves of spiral galaxies,
- Low-surface-brightness galaxies,
- Galactic structure and tidal streams,
- Template spectra for SDSS population synthesis.

In addition, there are programs led by other members in the collaboration. In the following, we give a brief overview of SDSS science currently pursued at Calar Alto.

5.1 Follow-up on SDSS Quasar and Low-Mass Star Candidates

At redshifts of 3 and higher quasars become increasingly red due to intervening absorption-line systems and are well separated from the bulk of other stellar or galaxy contaminants except for very cool, low-mass stars such as L and T dwarfs (Fan et al. 1999). Optical spectroscopy or infrared imaging help to distinguish quasar candidates not targeted by the SDSS due to, e.g., faintness. At MPIA we concentrate on the search for new high-redshift ($z > 4.5$) quasars through multi-color near-infrared observations of candidates pre-selected through optical SDSS photometry. In part, these observations aim at obtaining a complete sample of QSOs with optical and infrared colors. Furthermore, we follow up on z-band-only detections through additional J-band imaging. The resulting $(z - J)$ colors enable us to separate low-mass stars (mostly L dwarfs) from QSOs and to select targets for follow-up spectroscopy with 8-m to 10-m class telescopes.

SDSS spectroscopy is not usually obtained for science targets brighter than $r' \sim 14.5$ mag. Therefore, another quasar project executed at Calar Alto and other observatories aims at obtaining redshifts for quasars brighter than this magnitude limit.

Calar Alto spectroscopic follow-up is also being carried out for a sample of T Tauri stars and late-type dwarfs selected by their SDSS colors. We hope to ultimately establish complete magnitude-limited samples of low-mass stars,

an important precondition in deriving deep stellar and substellar luminosity functions. This project will also reveal whether the majority of the elusive T dwarfs exist as part of binary systems or in isolation in the field, confirm additional ancient, very metal-poor dwarfs, help to verify candidate T Tauri stars and thus improving their census, and provide a basis for further follow-up studies with large telescopes.

5.2 Galaxy Kinematics

SDSS spectra are of limited use for deriving internal galaxy kinematics since the spectra are obtained through fibers with a fixed circular diameter of $3''$. We use long-slit spectroscopy of an SDSS-selected galaxy sample spanning a a wide range of luminosity and color in order to obtain rotation curves and stellar velocity dispersions. SDSS provides distances, luminosities, colors, and morphological parameters for these galaxies. The longslit data will provide dynamical parameters — the depth and profile of galaxy potential wells — that can be incorporated into principal component analyses of the galaxy distribution. The data will also yield accurate estimates of the true scatter in bivariate "distance indicator" relations, most notably the Tully-Fisher relation, as a function of luminosity and wavelength. By combining the correlations between dynamical and photometric properties obtained from our sample with the distribution of photometric properties derived from the full SDSS redshift survey, we can estimate the distribution of galaxy-mass potential well depths, a fundamental prediction of galaxy formation theories. This data set may also be useful for many other investigations, including searches for new distance-indicator relations, studies of the distribution of galaxy angular momenta, and identification of dynamically peculiar systems.

5.3 Low-Surface-Brightness Galaxies and Dwarf Galaxies

This project follows up on low-surface-brightness (LSB) and dwarf galaxies that we detect in the SDSS images based on adaptive filters and other techniques. The homogeneity, area coverage, and depth of the SDSS makes it uniquely suited for improving the census of these faint objects. With many of the LSB and dwarf galaxies too faint to be targeted by SDSS spectroscopy, our spectroscopic follow-up studies allow us to determine distances, abundances, kinematics, and to some extent even star formation histories. This will vastly increase the available data on low-mass galaxies and enable us to carry out a thorough study of galaxy evolution and impacting factors (such as environment) with unprecedented comprehensiveness.

5.4 Galactic Structure and Tidal Streams

The SDSS data quality far exceeds the capabilities of photographic all-sky surveys, which are less deep, have poorer resolution, suffer from large-scale

inhomogeneities and center-to-edge plate variations, and are limited in area coverage. This makes it an excellent tool for Galactic structure studies as described earlier. Still, the SDSS is limited in depth. Also, it does not obtain stellar spectra on a regular basis.

Calar Alto follow-up on tidal streams comprises both deep imaging and spectroscopy. Deep imaging is used to obtain luminosity functions in streams and the parent object, and to study mass segregation. Spectroscopic follow-up is used both to establish kinematic membership of stars in streams and to measure the velocity dispersion, which yields crucial constraints for dynamical modelling.

5.5 Calibration and Modelling

The interpretation of both SDSS photometry and spectroscopy requires a thorough understanding of the SDSS calibration. Currently the SDSS calibration is still considered preliminary, subject to additional improvements prior to the first large public data release. This affects the absolute calibration of the SDSS photometry and the flux calibration of the spectroscopy. E.g., a still unanswered question is how SDSS $3''$ fibre spectra of point sources or extended sources compare to regular longslit spectra of the same sources. Another potential concern is how well the combination of SDSS spectra obtained in the red and in the blue channel works.

A more general topic is the interpretation of spectroscopic indices measurable in galaxies, in particular Balmer line ratios as age indicators and Lick indices. Population synthesis models may yield different ages even for simple stellar populations than does detailed color-magnitude diagram modelling of their resolved stellar populations. This is a particularly severe problem that becomes difficult to assess in galaxies where only the integrated light can be measured. Age and metallicity indicators like the Lick indices may be subject to errors owing to the impact of, e.g., horizontal branch morphology variations or mixed-age populations rather than single-age populations.

We are working on establishing a spectroscopic template database at SDSS resolution. Our targets include both stars with well-established metallicities and star clusters with known ages, reddenings, distances, and abundances. This effort is being carried out at Calar Alto and other observatories and will be vital for the interpretation of SDSS spectra and SDSS-specific population synthesis models.

6 Outlook

The SDSS is mapping one quarter of the sky through multi-color imaging and spectroscopy at unprecedented area coverage and homogeneity. The reduced and calibrated data will become available to the entire astronomical community over the next five years. They will undoubtedly spawn a wide range of discoveries ranging from cosmology to star formation. This unique

vast database will change the way we do astronomy and provides a virtual observatory in itself.

There are efforts to carry out southern large-sky surveys. The 2dF QSO Redshift Survey (2QZ) will obtain redshifts for more than 25,000 quasars. ESO is building the VLT Survey Telescope (VST), a 2.5-m telescope for optical wide-field imaging. The British Visible & Infrared Survey Telescope for Astronomy (VISTA) will provide both optical and infrared imaging. VISTA will reach approximately five times deeper than the SDSS in the northern hemisphere and will surpass DENIS and 2MASS in depth as well.

The SDSS and the ongoing/planned southern surveys are complemented by similarly large databases in other wavelength ranges such as 2MASS, FIRST, HIPASS/HIJASS, RASS, etc. The combination of multi-wavelength fluxes, velocity and distance information may lead to discoveries that we can not yet envision.

Acknowledgements

The Sloan Digital Sky Survey (SDSS) is a joint project of The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington. Apache Point Observatory, site of the SDSS telescopes, is operated by the Astrophysical Research Consortium (ARC).

Funding for the project has been provided by the Alfred P. Sloan Foundation, the SDSS member institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, Monbusho, and the Max Planck Society. The SDSS Web site is `http://www.sdss.org/`.

References

Anderson, S.F., Fan, X., Richards, G.T., Schneider, D.P., Strauss, M.A., et al. 2001, AJ, submitted

Blanton, M.R., Dalcanton, J.D., Eisenstein, D., Loveday, J., Strauss, M.A., et al. 2001, AJ, 121, 2358

Dalcanton, J., Kent, S., Okamura, S., Williams, G.V., Tichy, M., et al. 1999, IAU Circ., 7194, 1

Fan, X., Knapp, G.R., Strauss, M.A., Gunn, J.E., Lupton, R.H., et al. 2000, AJ, 119, 928

Fan, X., White, R.L., Davis, M., Becker, R.H., Strauss, M.A., et al. 2000, AJ, 120, 1167

Fan, X., Strauss, M.A., Schneider, D.P., Gunn, J.E., Lupton, R.H., et al. 2001, AJ, 121, 54

Fischer, P., McKay, T.A., Sheldon, E., Connolly, A., Stebbins, A., et al. 2000, AJ, 120, 1198

Fukugita, M., Ichikawa, T., Gunn, J.E., Doi, M., Shimasaku, K., & Schneider, D.P. 1996, AJ, 111, 1748

Goto, T., Sekiguchi, M., Kim, R.S.J., Bahcall, N.A., Annis, J., et al. 2001, AJ, submitted

Gunn, J.E., Carr, M., Rockosi, C., Sekiguchi, M., Elms, B.B., et al. 1998, AJ, 116, 3040

Harris, H.C., Hansen, B.M.S., Liebert, J., Vanden Berk, D.E., Anderson, S.F., et al. 2001, ApJ, 549, L109

Ibata, R., Irwin, M., Lewis, G.F., & Stolte, A. 2001, ApJ, 547, L133

Ivezić, Ž, Goldston, J., Finlator, K., Knapp, G.R., Yanny, B., et al. 2000, AJ, 120, 963

Kirkpatrick, J.D., Reid, I.N., Liebert, J., Cutri, R.M., Nelson, B., et al. 1999, ApJ, 519, 802

Leggett, S.K., Geballe, T.R., Fan, X., Schneider, D.P., Gunn, J.E., et al. 2000, ApJ, 536, L35

Lupton, R.H., Gunn, J.E., & Szalay, A.S. 1999, AJ, 118, 1406

Odenkirchen, M., Grebel, E.K., Rockosi, C.M., Dehnen, W., Ibata, R., et al. 2001, ApJ, 548, L165

Richards, G.T., Fan, X., Schneider, D.P., Vanden Berk, D.E., Strauss, M.A., et al. 2001a, AJ, 121, 2308

Richards, G.T., Weinstein, M.A., Schneider, D.P., Fan, X., Strauss, M.A., et al. 2001b, AJ, submitted

Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525

Schneider, D.P., Fan, X., Strauss, M.A., Gunn, J.E., Richards, G.T., et al. 2000, AJ, 120, 2183

Sheldon, E.S., Annis, J., Böhringer, H., Fischer, P., Frieman, J.A., et al. 2001, ApJ, in press

Strauss, M.A., Fan, X., Gunn, J.E., Leggett, S.K., Geballe, T.R., et al. 1999, ApJ, 522, L61

Tsvetanov, Z.I., Golimowski,D.A., Zheng, W., Geballe, T.R., Leggett, S.K., et al. 2000, ApJ, 531, L61

Vanden Berk, D.E., Richards, G.T., Bauer, A., Strauss, M.A., Schneider, D.P., et al. 2001, AJ, submitted

Yanny, B., Newberg, H.J., Kent, S., Laurent-Muehleisen, S.A., Pier, J.R., et al. 2000, ApJ, 540, 825

York, D.G., Adelman, J.E., Anderson, S.F., Anderson, J., Annis, J., et al. 2000, AJ, 120, 1579